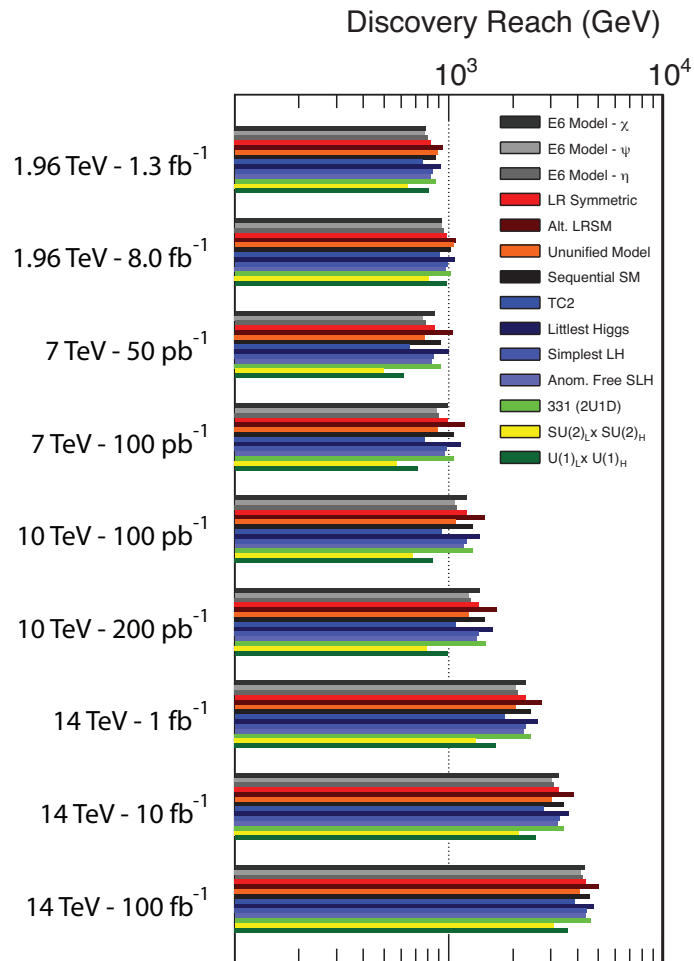


# Model Independent $Z'$ Sensitivities



Diener et al., 0910.1334

- Motivations
- Model independent analysis
- Couplings
- Present and future constraints and diagnostics
- References

- Extensive physics implications, especially for TeV-scale  $Z'$ 
  - Extended Higgs/neutralino sector (LHC cascades, dark matter)
  - Quasi-chiral exotics (anomalies; may be long-lived)
  - Sparticle/exotics factory
  - Possible tree-level FCNC (may compete with SM loops)
  - Origin of  $\nu$  mass (Majorana, Dirac, or ordinary-sterile mixing)
  - Can allow electroweak baryogenesis
  - Possible  $Z'$  mediation of SUSY breaking

## Standard Model with Additional $U(1)'$

$$-L_{\text{NC}} = \underbrace{eJ_{em}^\mu A_\mu + g_1 J_1^\mu Z_{1\mu}^0}_{\text{SM}} + \sum_{\alpha=2}^{n+1} g_\alpha J_\alpha^\mu Z_{\alpha\mu}^0$$

$$J_\alpha^\mu = \sum_i \bar{f}_i \gamma^\mu [\epsilon_L^\alpha(i) P_L + \epsilon_R^\alpha(i) P_R] f_i$$

- $\epsilon_{L,R}^\alpha(i)$  are  $U(1)_\alpha$  charges of the left and right handed components of fermion  $f_i$  (chiral for  $\epsilon_L^\alpha(i) \neq \epsilon_R^\alpha(i)$ )
- $g_{V,A}^\alpha(i) = \epsilon_L^\alpha(i) \pm \epsilon_R^\alpha(i)$
- May specify left chiral charges for fermion  $f$  and antifermion  $f^c$

$$\epsilon_L^\alpha(f) = Q_{\alpha f} \quad \epsilon_R^\alpha(f) = -Q_{\alpha f^c}$$

$$Q_{1u} = \frac{1}{2} - \frac{2}{3} \sin^2 \theta_W \quad \text{and} \quad Q_{1uc} = +\frac{2}{3} \sin^2 \theta_W$$

- Family universal for  $\epsilon_{L,R}^2(u) = \epsilon_{L,R}^2(c) = \epsilon_{L,R}^2(t)$   
(and  $(d, s, b), (e, \mu, \tau), (\nu_e, \nu_\mu, \nu_\tau)$ )
  - Otherwise, FCNC induced by fermion mixing

## Motivations for a $Z'$

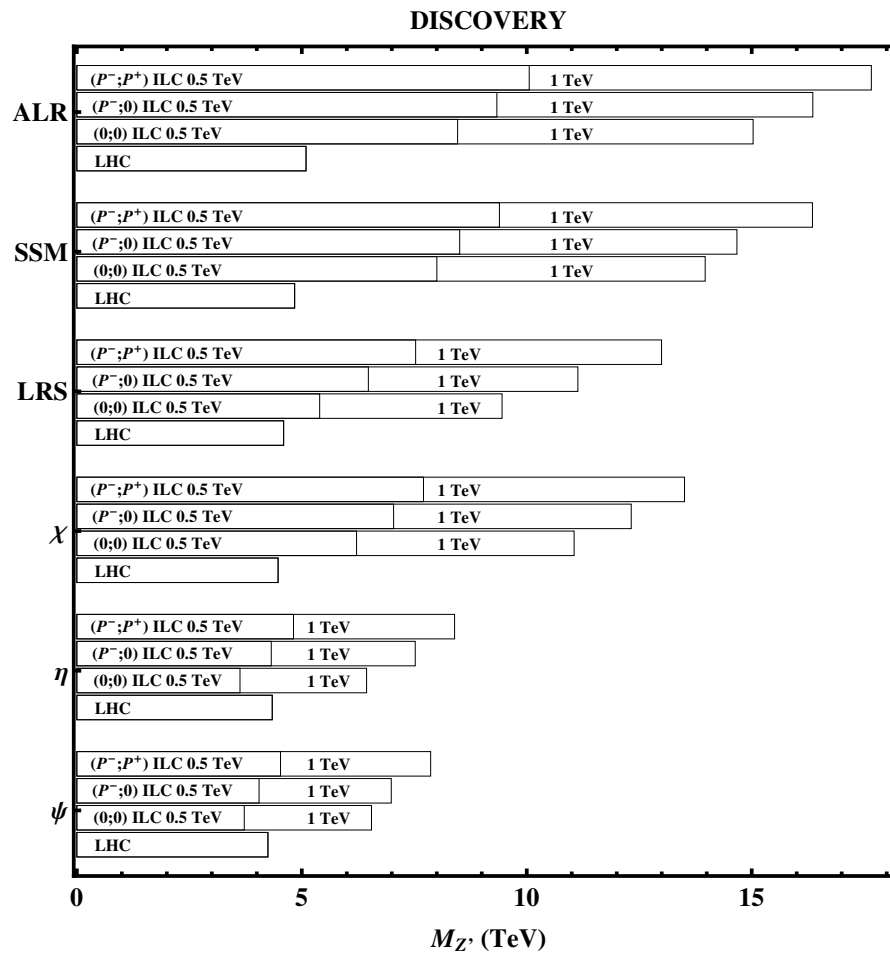
- Occur in most extensions of standard model, often at TeV scale
- **Strings/GUTS** (large underlying groups;  $U(n)$  in Type Ila)
  - Harder to break  $U(1)'$  factors than non-abelian (remnants)
  - Supersymmetry:  $SU(2) \times U(1)$  and  $U(1)'$  breaking scales *both* set by SUSY breaking scale (unless flat direction)
  - Elegant solution to  $\mu$  problem
- **Alternative electroweak model/breaking (TeV scale): DSB, Little Higgs, extra dimensions** (Kaluza-Klein excitations,  $M \sim R^{-1} \sim 2 \text{ TeV} \times (10^{-17} \text{ cm}/R)$ ), **left-right symmetry**
- **Connection to quasi-hidden sectors** (dark; SUSY breaking)

## Model-Independent Analyses

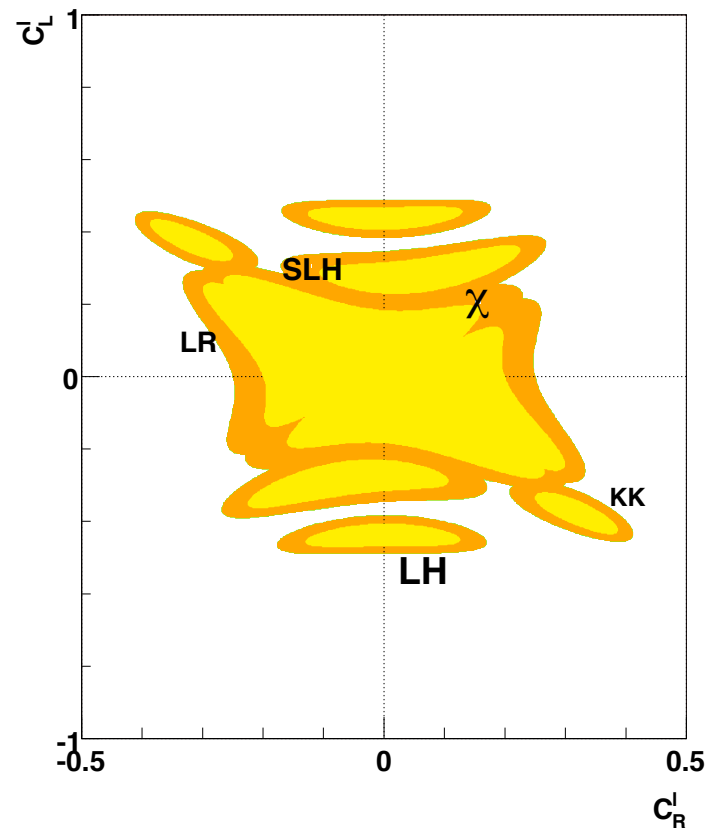
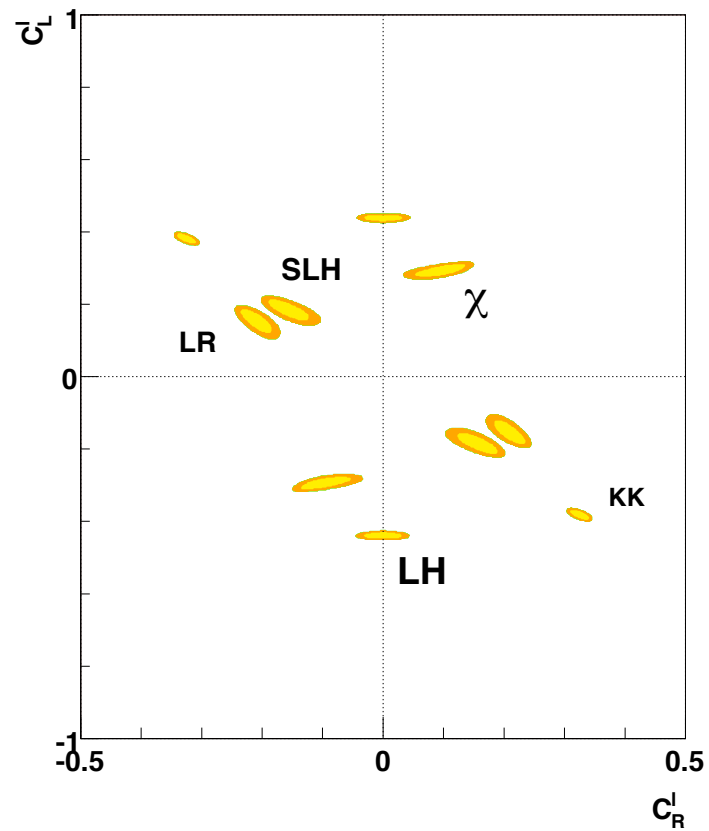
- Extensive studies of precision electroweak (mass, mixing), Tevatron, LHC, ILC, possible FCNC
- Mostly for benchmark models (sequential  $Z'$ ;  $E_6$ ;  $T_{3R}/B - L$ ; anomaly-free; DSB; family-nonuniversal; leptophobic; kinetic mixing;  $\dots$ )
- Model-independent couplings (possibly family universal)
  - Important for probing class of model
  - Formalism/diagnostics developed in early 1990s (needs updating)
  - Many parameters, even for family universal:  $Q_L, L_L, u_L^c, d_L^c, e_L^+$  charges ( $g'$  absorbed or by convention);  $M_{Z'}, \Gamma_{Z'}, \theta$ ; exotic, Higgs,  $\nu_R$ , family nonuniversal, etc

- Updated model-independent analysis of LHC/ILC sensitivities and diagnostic possibilities (with Tao Han, Zhen Liu)
- Comparison to flavor physics for family nonuniversal (with Cheng-Wei Chiang, Jusak Tandean)
- Focus on TeV-scale with  $\sim$ electroweak-strength couplings to  $q, \ell$
- Full analysis of two benchmarks (for ILC at 500 GeV and 1 TeV):
  - $M_{Z'} = 3 \text{ TeV}$  (dielectron resonance at LHC with rapidity,  $A_{FB}$ , etc; ILC interference with  $Z, \gamma$ )
  - $M_{Z'} = 6 \text{ TeV}$  (ILC interference only)
- Sensitivity? How much can one learn about parameters such as  $\epsilon_R(e)/\epsilon_L(L)$ ,  $\epsilon_R(u)/\epsilon_L(Q)$ ,  $\epsilon_R(d)/\epsilon_L(Q)$  and new physics decay channels?

# ILC/CLIC Sensitivities in Specific Models

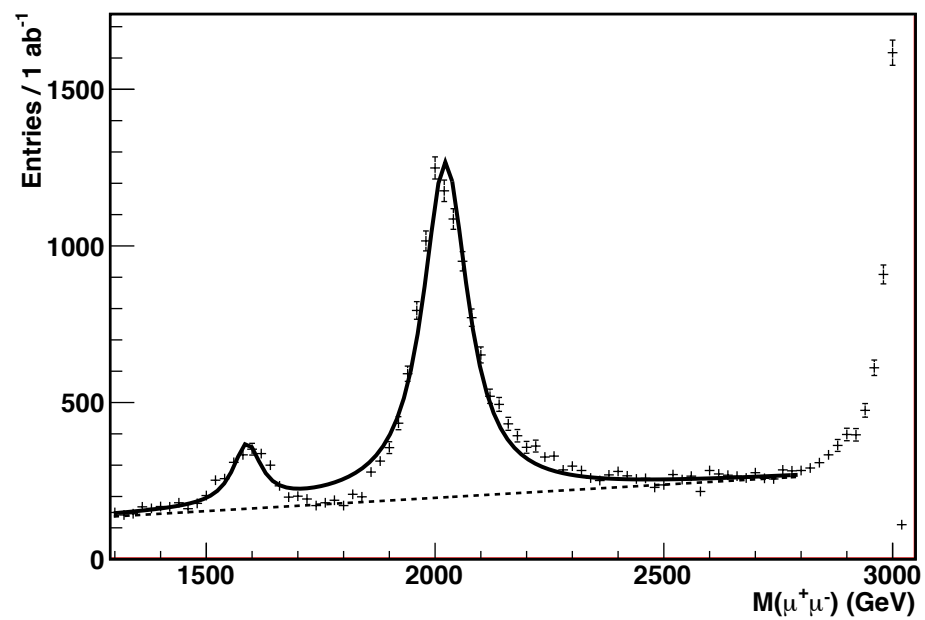


Osland et al, 0912.2806; 95%

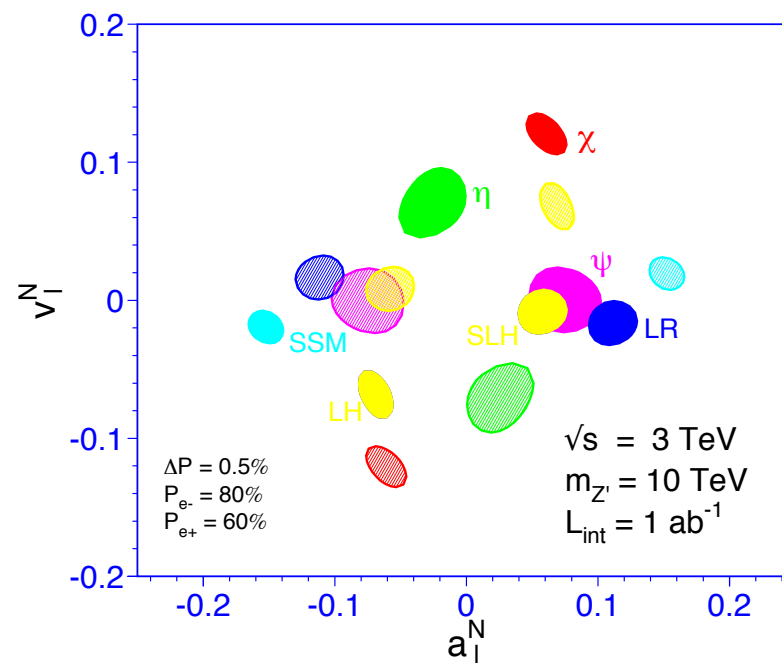


Godfrey ea, 0511335

$M_{Z'} = 2(4) \text{ TeV}$ ; ILC at 500 GeV,  $1000 \text{ fb}^{-1}$ ,  $P_{e^-, e^+} = 80(60)\%$ ; 95%



CLIC, 1202.5940

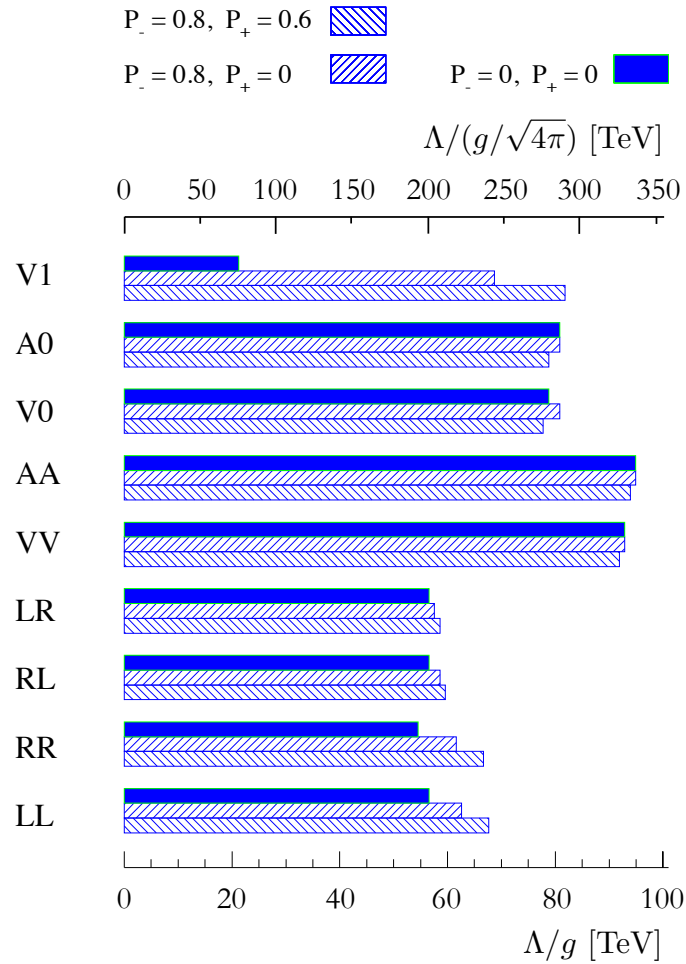


## References

- **CLIC:** *Physics and Detectors at CLIC: CLIC Conceptual Design Report*, L. Linssen *et al.*, [\[1202.5940\]](#)
- **ILC:** *ILC Physics DBD*
- **LHC:** *Z' Physics at the LHC*, from P. Nath *et al.*, *The Hunt for New Physics at the Large Hadron Collider*, Nucl. Phys. Proc. Suppl. 200-202, 185 (2010) [\[1001.2693\]](#)
- **LHC/ILC:** *Physics Interplay of the LHC and the ILC*, G. Weiglein *et al.*, Phys. Rept. 426, 47 (2006) [\[0410364\]](#)
- **Theory:** *The Physics of Heavy Z' Gauge Bosons*, PL, Rev. Mod. Phys. 81, 1199 (2009) [\[0801.1345\]](#)
- **E<sub>6</sub> Models:** J. Hewett and T. Rizzo, Phys. Rept. 183, 193 (1989)
- **Model Independent formalism:** [\[9303299\]](#), [\[9312329\]](#), [\[9501390\]](#)
- More extensive discussion in Duke talk [Non-Standard Gauge Bosons](#)

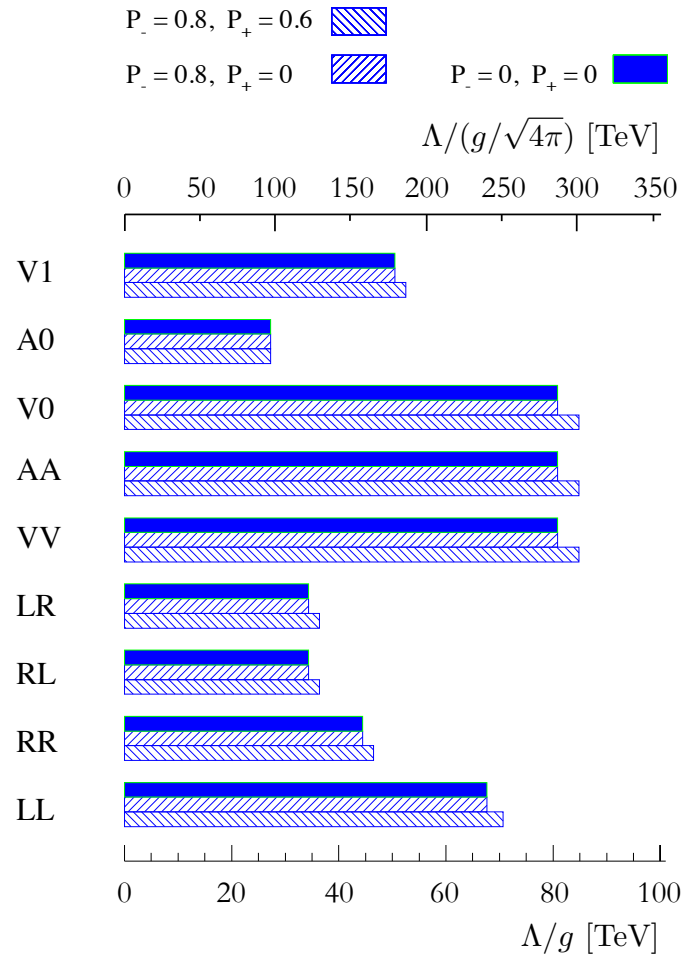
CLIC 3 TeV, 1 ab<sup>-1</sup>

$e^+e^- \rightarrow \mu^+\mu^-$



CLIC 3 TeV, 1 ab<sup>-1</sup>

$e^+e^- \rightarrow b\bar{b}$



**CLIC, 1202.5940 ( $g \sim 0.46$  for comparison)**

- $[SU(2), U(1)'] = 0 \Rightarrow \epsilon_L^2(u_i) = \epsilon_L^2(d_i), \epsilon_L^2(e_i) = \epsilon_L^2(\nu_i)$
- Can choose  $g_2$  by convention (or absorb into couplings)
- $\Gamma_{Z_2}$  may be increased by decays into sparticles, exotics, invisible

## Present and future constraints and diagnostics

- Precision electroweak (low energy WNC,  $Z$ -pole, LEP2, Tevatron, LHC)
  - Stringent limits on  $Z - Z'$  mixing; mass limits superseded by Tevatron, LHC
  - Future: JLab and other ( $Q_{\text{weak}}$ , Moller, SOLID); Giga- $Z$

## The Tevatron and LHC

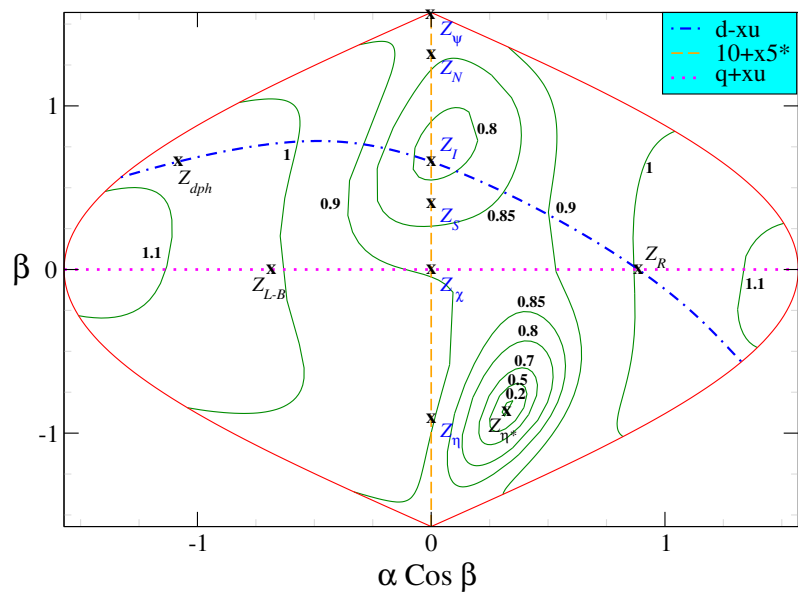
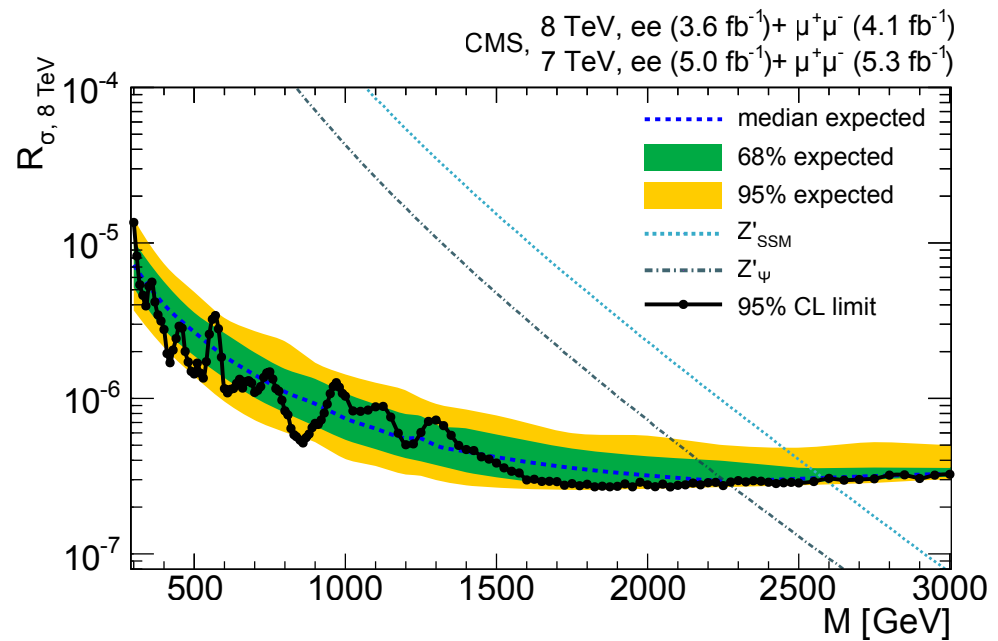
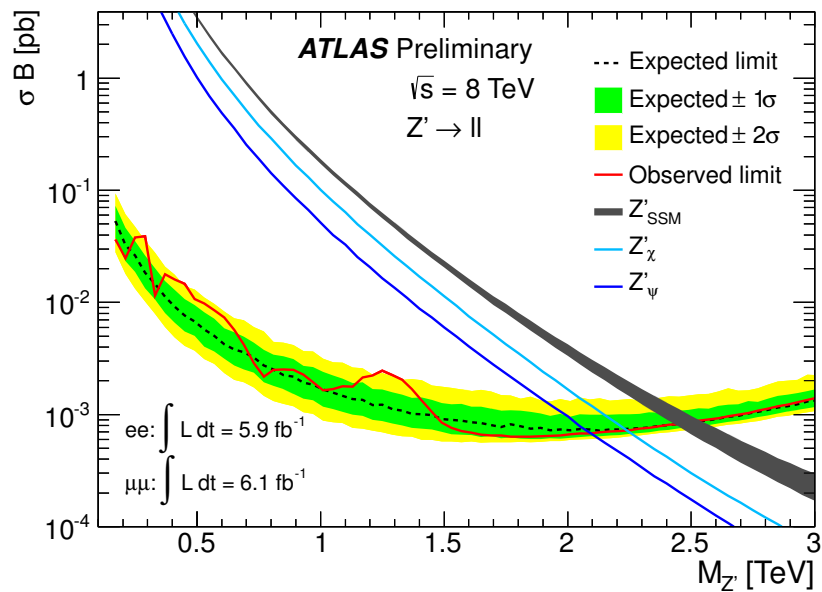
- Resonance in  $pp, \bar{p}p \rightarrow e^+e^-, \mu^+\mu^-, \dots AB \rightarrow Z_\alpha$  in narrow width:

$$\frac{d\sigma}{dy} = \frac{4\pi^2 x_1 x_2}{3M_\alpha^3} \sum_i \left( f_{q_i}^A(x_1) f_{\bar{q}_i}^B(x_2) + f_{\bar{q}_i}^A(x_1) f_{q_i}^B(x_2) \right) \Gamma(Z_\alpha \rightarrow q_i \bar{q}_i)$$

$$\Gamma_{f_i}^\alpha \equiv \Gamma(Z_\alpha \rightarrow f_i \bar{f}_i) = \frac{g_\alpha^2 C_{f_i} M_\alpha}{24\pi} \left( \epsilon_L^\alpha(i)^2 + \epsilon_R^\alpha(i)^2 \right)$$

$$x_{1,2} = (M_\alpha / \sqrt{s}) e^{\pm y} \quad C_{f_i} = \text{color factor}$$

- Also dijet,  $t\bar{t}$ , etc: strongly coupled resonances
- Corrections for QCD/interference, etc  
(e.g., Petriello ea, 0801.4389; Erler ea, 1103.2659)



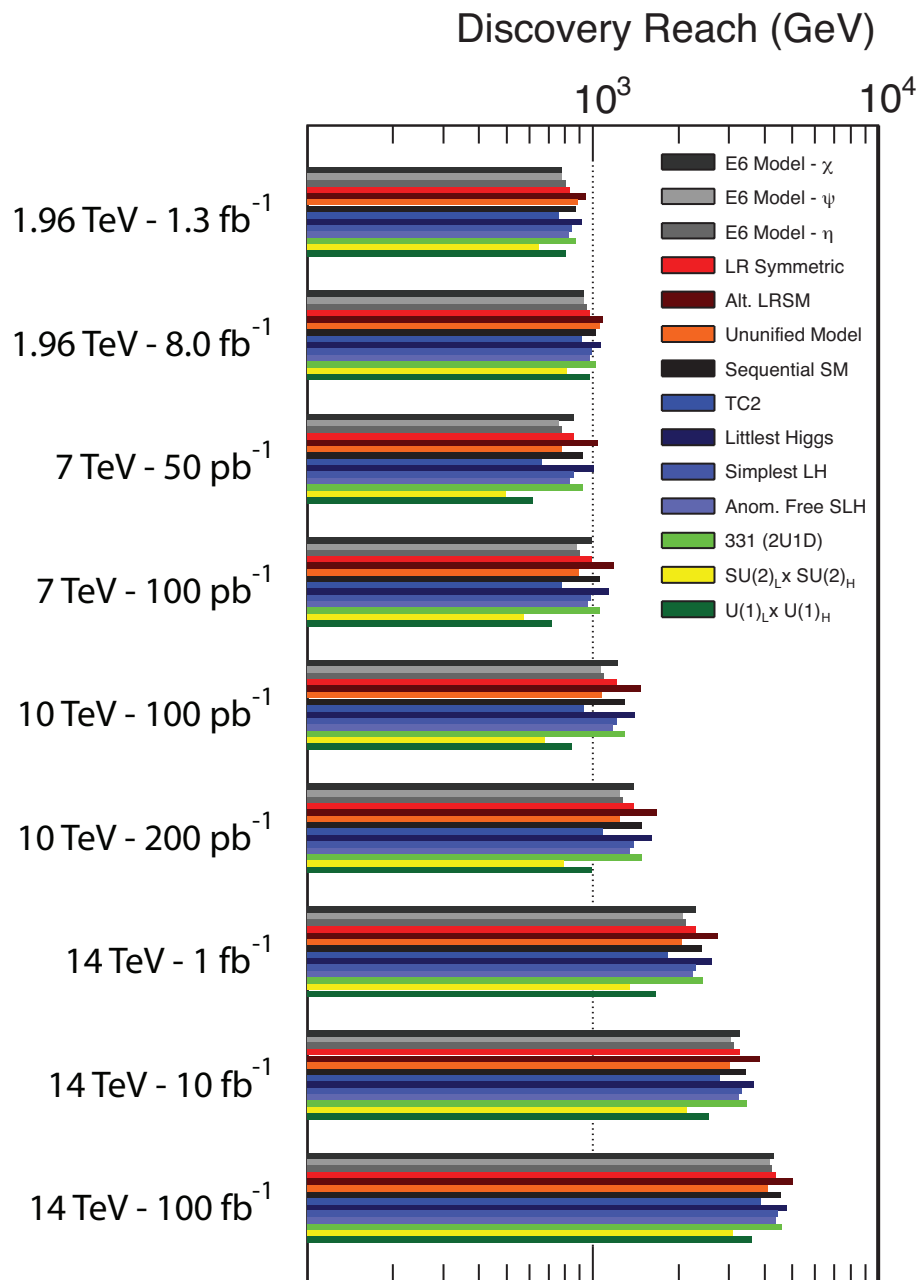
$$Z' = \cos \alpha \cos \beta Z_\chi + \sin \alpha \cos \beta Z_Y + \sin \beta Z_\psi$$

Erler et al, 1103.2659

- LHC discovery to  $\sim 4 - 5$  TeV
  - Spin-0 (Higgs), spin-1 ( $Z'$ ), spin-2 (Kaluza-Klein graviton) by angular distribution, e.g.,

$$\frac{d\sigma_{Z'}^f}{d\cos\theta^*} \propto \frac{3}{8}(1 + \cos^2\theta^*) + A_{FB}^f \cos\theta^* \quad [\text{for spin-1}]$$

- Rates (total width) dependent on whether sparticle and exotic channels open  
 (  $\Gamma_{Z'}/M_{Z'} \sim 0.01 \rightarrow 0.05$  for  $E_6$  )  
 (Kang ea 0412190, Chang ea 1107.1133)



Diener et al., 0910.1334; 5 events/dilepton channel  
 Snowmass Energy Frontier (BNL), April 5, 2013

Paul Langacker/LianTao Wang

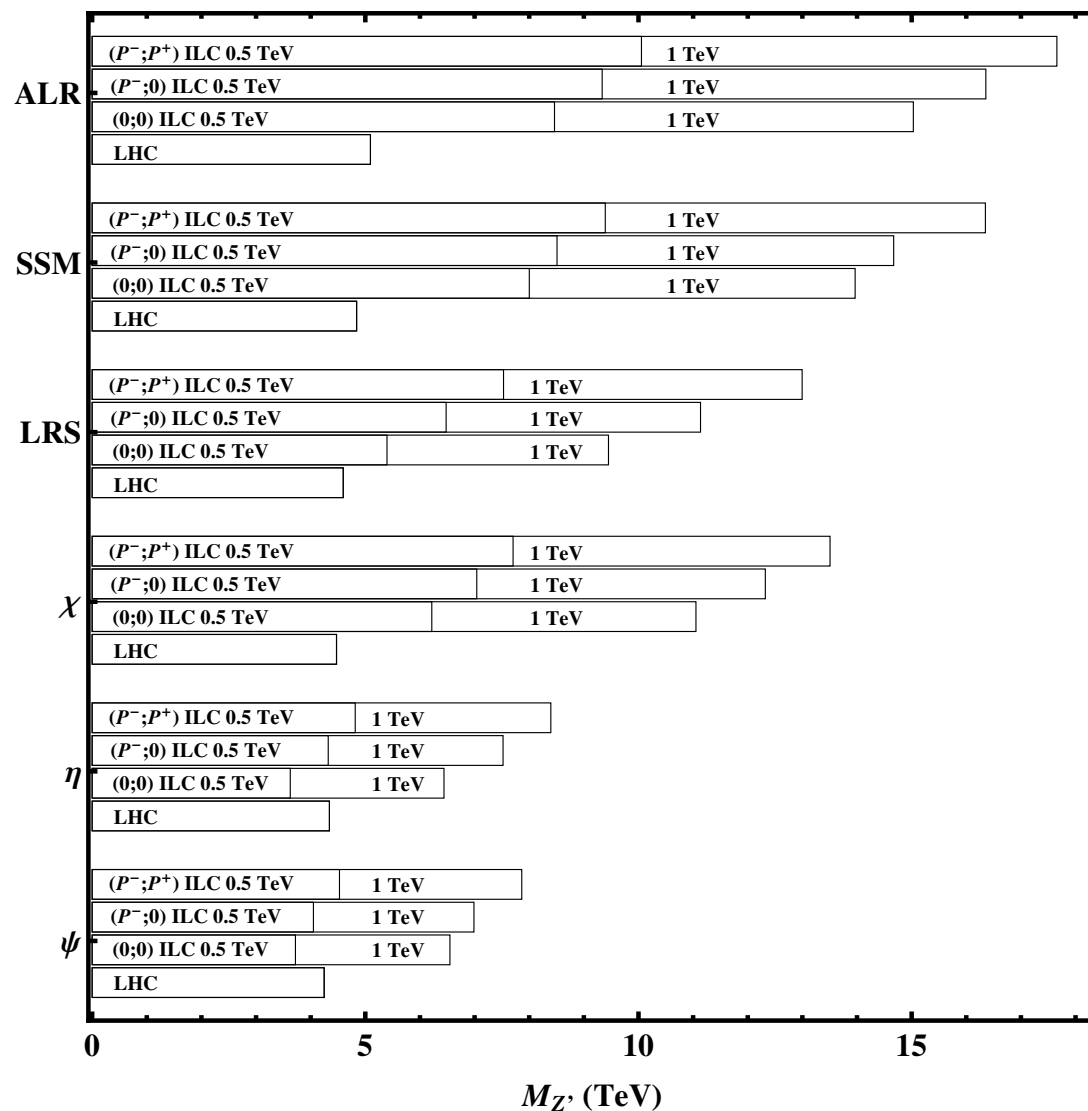
## $e^-e^+$ Linear Colliders: ILC, CLIC

- $e^-e^+ \rightarrow f\bar{f}$  ( $\gamma, Z, Z'$  interference in  $\sigma, A_{F,B}, P_{e^-,e^+}$ , mixed )

$$\epsilon_{L,R}^\alpha(f) \rightarrow \epsilon_{L,R}^\alpha(f) \frac{M_\alpha}{\sqrt{M_\alpha^2 - s}}$$

- Possible window for resonance at CLIC?
- Regimes
  - Discovery/mass at LHC (4-5 TeV)
  - Too heavy for LHC (sensitive to  $7-10 \sqrt{s}$ )
  - Also:  $Z$ -pole (Giga- $Z$ )

# DISCOVERY

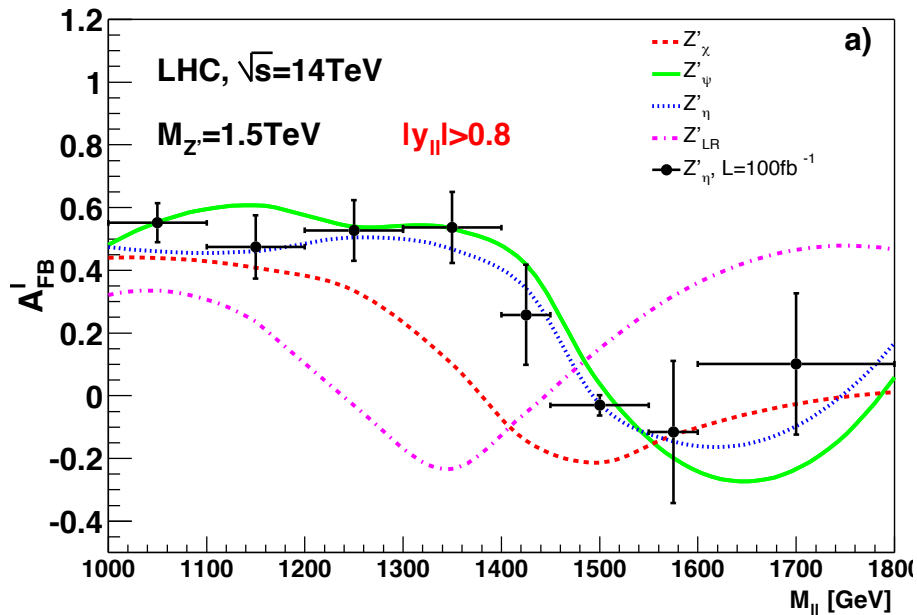


Osland et al., 0912.2806; 95%

# Diagnostics of $Z'$ Couplings

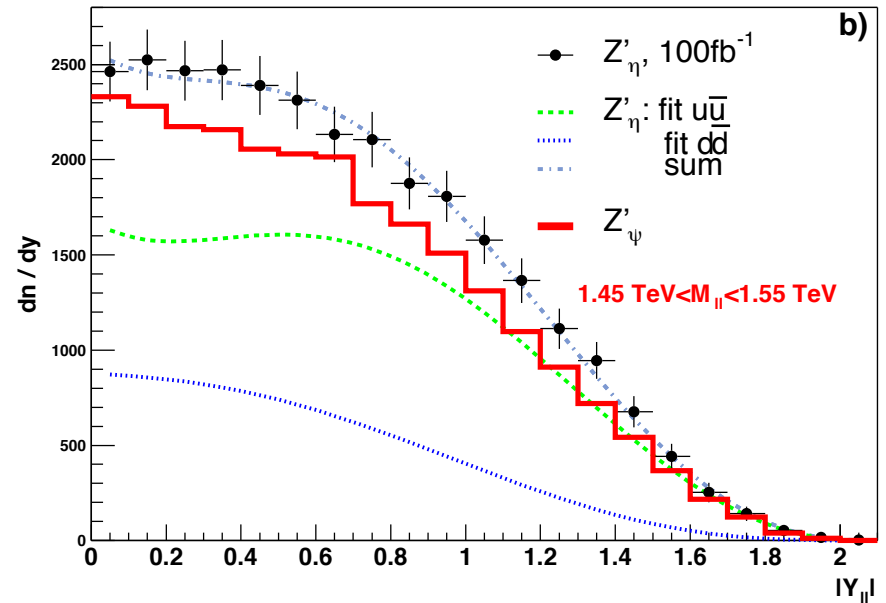
- LHC diagnostics to 2-2.5 TeV
- Forward-backward asymmetries and rapidity distributions in  $\ell^+\ell^-$

Forward backward asymmetry measurement



(LHC/ILC, hep-ph/0410364)

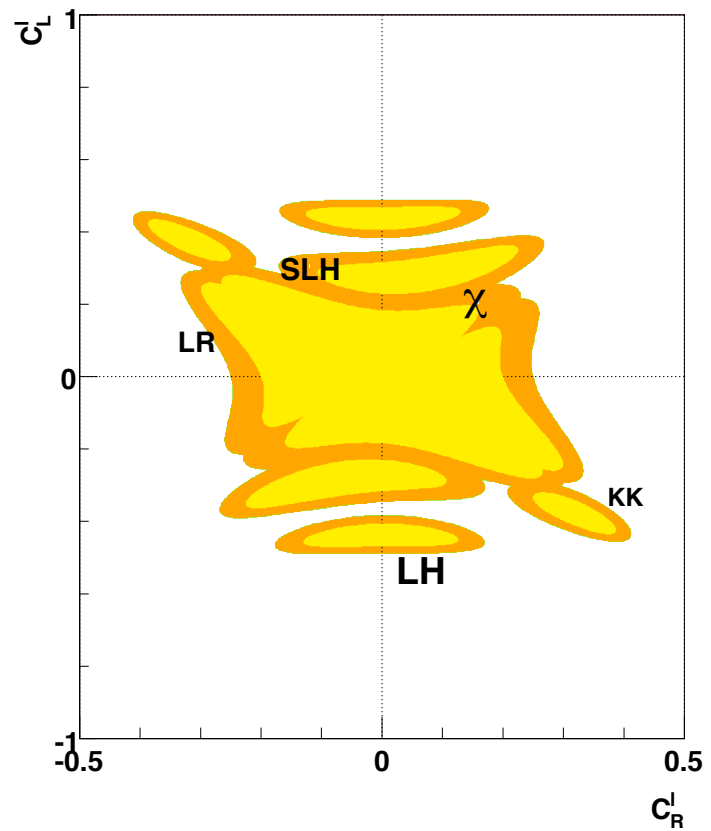
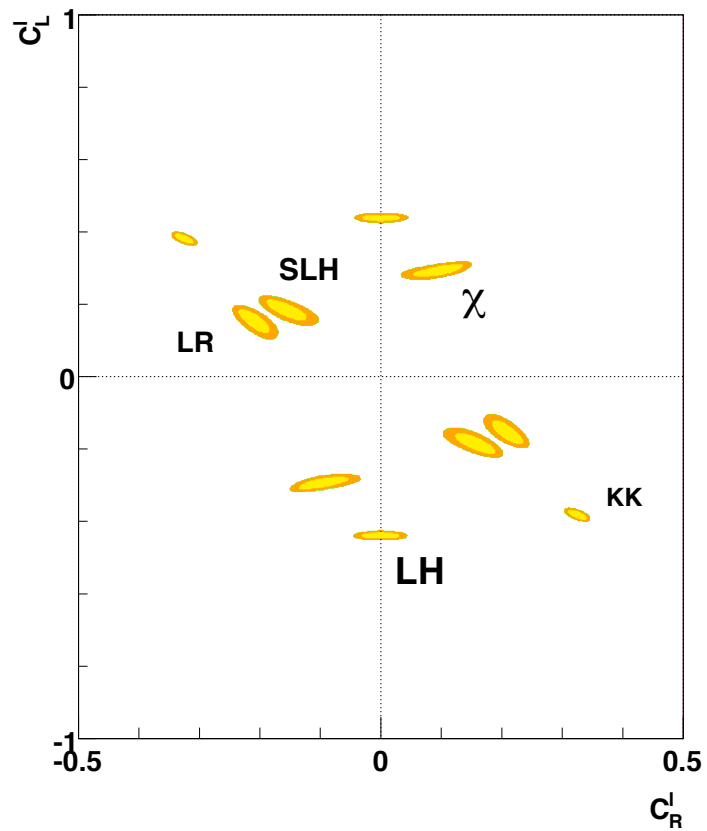
Rapidity distribution



- Other two body decays ( $jj, \bar{b}b, \bar{t}t, e\mu, \tau^+\tau^-$ )
- Lineshape:  $\sigma_{Z'}B_\ell, \Gamma_{Z'}$
- $\tau$  polarization
- Associated production  $Z'Z, Z'W, Z'\gamma$
- Rare (but enhanced) decays  $Z' \rightarrow W\bar{f}_1f_2$  (radiated  $W$ )
- $Z' \rightarrow W^+W^-, Zh$ , or  $W^\pm H^\mp$ : small mixing compensated by longitudinal  $W, Z$

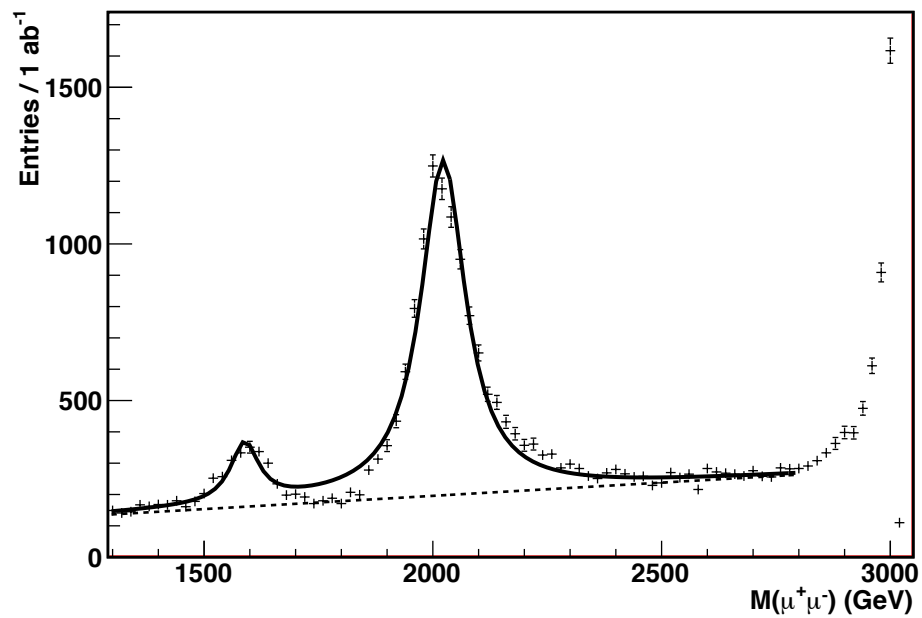
$$\Gamma(Z' \rightarrow W^+W^-) = \frac{g_1^2\theta^2 M_{Z'}}{192\pi} \left(\frac{M_{Z'}}{M_Z}\right)^4 = \frac{g_2^2 C^2 M_{Z'}}{192\pi}$$

- Exotic decays: multileptons ( $\ell\bar{\ell}\ell\bar{\ell}$  via RPV;  $6\ell$  via  $ZH'$ );  $ggg, gg\gamma$  (loops); same-sign dileptons (heavy Majorana  $\nu$ ); invisible; sparticles/exotics (SUSY factory)
- Upgrade to hadronic polarization would be useful

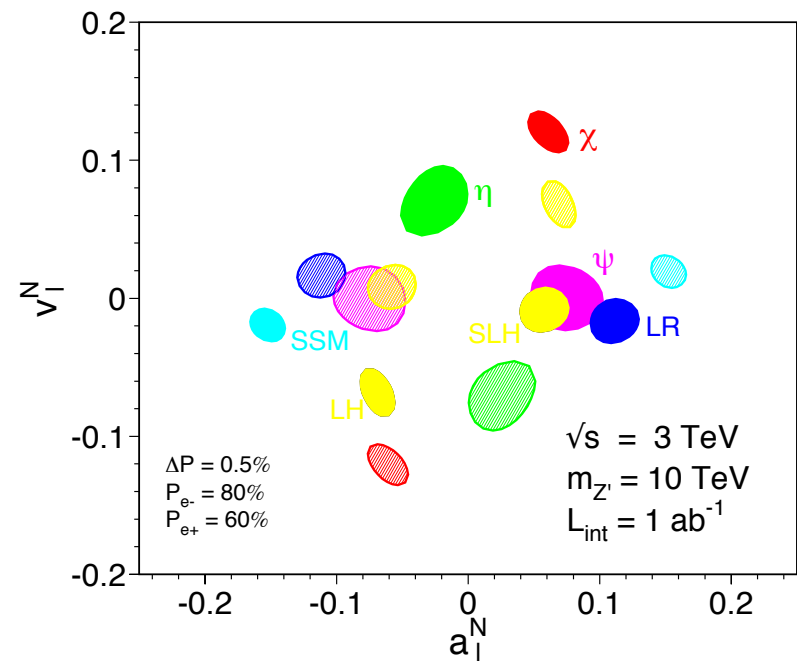


**Godfrey ea, 0511335**

$M_{Z'} = 2(4) \text{ TeV}$ ; ILC at 500 GeV,  $1000 \text{ fb}^{-1}$ ,  $P_{e^-, e^+} = 80(60)\%$ ; 95%



CLIC, 1202.5940



- Benchmarks vs model independent studies of couplings  
(parametrization: Cvetič et al., 9501390, 9312329, 9303299)
- LHC/ILC (CLIC) diagnostics complementary
- Extensive references in
  - *The Hunt for New Physics at the Large Hadron Collider*, 1001.2693
  - *The Physics of Heavy  $Z'$  Gauge Bosons*, 0801.1345